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Advances in Space Research 37 (2006) 2172–2177
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

Simultaneous determination of aerosol- and surface characteristics from top-of-atmosphere reflectance using MERIS on board of ENVISAT

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Received 28 October 2004; received in revised form 10 March 2006; accepted 11 March 2006

Abstract

The determination of aerosol optical thickness (AOT) from nadir scanning multi-spectral radiometers, like SeaWiFS, MERIS or MODIS, requires the separation of spectral atmospheric and surface properties. Since SeaWiFS and MERIS do not provide information at 2.1 μm, like MODIS, the estimation of the surface reflectance cannot be made by the cross correlation approach described by Kaufman et al., 1997. The BAER approach (Bremen AErosol Retrieval), von Hoyningen-Huene et al., 2003, uses a linear mixing model of spectra for 'green vegetation' and 'bare soil', tuned by the NDVI, determining an apparent surface to enable this separation of aerosol and surface properties from VIS and NIR channels. Thus AOT can be derived over a wide range of land surfaces for wavelengths <0.67 μm. Using MERIS L1 data over Europe, the AOT retrieved is comparable with ground-based observations, provided by AERONET. Regional variation of AOT can be observed, showing the atmospheric variability for clear sky conditions by: large scale variation of aerosol turbidity, regional pollution, urban regions, effects of contrails and cases of aerosol-cloud interaction. Simultaneously with the spectral AOT also spectral surface reflectance is obtained, where all atmospheric influences have been considered (molecules, aerosols and absorbing gases (O_3)) for channels with wavelengths <0.67 μm. The AOT is extrapolated by Angström power law to NIR channels and the atmospheric correction for land surface properties is performed, enabling the further investigation of land use and spectral land properties.

Keywords: Remote sensing; Aerosol optical thickness; Surface reflectance; MERIS

1. Introduction

There are several objectives for satellite observations of properties of atmospheric aerosols, especially the spectral aerosol optical thickness (AOT). They are listed below:

(1) Atmospheric correction. For surface remote sensing (both over ocean and land) the contribution to the satellite signal by gases, molecules and aerosols needs to be removed. One of the most variable influences comes from atmospheric aerosol. Especially, the knowledge and regional variability of AOT and its spectral properties enables the determination of the variable influence of aerosol within the atmosphere. The atmospheric correction yields spectral surface reflectance, required for land use applications and

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doi:10.1016/j.asr.2006.03.017

investigations on vegetation types and status. Projects on surface reflectance and surface albedo, cf. Justice et al., 1998, Schaaf et al., 2002, Schröder et al., 2005 use AOT retrievals for atmospheric correction.

(2) Climate research. The determination of the direct radiative effect of the aerosol is based directly on the knowledge of the spectral AOT. Regional and temporal distribution of AOT provides information on source and sinks of aerosol, its seasonal behavior and transportation. Moreover, the aerosol has indirect effects on cloud formation by aerosol-cloud-interaction.

(3) Environmental control. Spectral AOT is the only quantitative indicator from satellite observations for atmospheric pollution by particulate matter and the transport of these pollutants. It yields information on effective radius, an essential information to convert AOT into columnar aerosol mass. Kokhanovsky et al., 2006 determines information on particulate matter from spectral AOT.

Satellite observations with nadir scanning radiometers can provide the regional and temporal distribution of AOT. This is the basis for further conclusions on aerosol transports, atmospheric aerosol loading and aerosol types. Thus, status and variability of aerosol can be investigated much better as compared to the ground-based networks, because satellite observations are available globally.

Multi-wavelength observations yield the spectral behavior of AOT. The observed spectral behavior gives indications for the prevailing aerosol type. Also the spectral slope can be related to an effective radius of the aerosol. Since the most aerosol sources are over land, retrieval methods are required to give spectral AOT not only over ocean surfaces with low and less variable surface reflectance, but also over land. Retrieval methods must be able to detect the AOT also over more variable land surfaces. Magnitude of AOT and spectral behavior enables observations of aerosol effects of anthropogenic pollution, mineral dust, biomass burning and the status of general atmospheric turbidity caused by aerosols.

Atmospheric correction needs to consider the variability of the spectral aerosol effects. Thus the spectral contribution of aerosol scattering and absorption has to be removed before investigations of land use can be made. These require the determination of spectral surface properties and their variations free of atmospheric effects.

The determination of AOT over land requires low and known surface reflectance. Over land, lower values for the surface reflectance are given in the green and blue bands of the spectrum. Therefore, the determination of AOT is performed mostly for wavelengths below 0.670 μm. Multi-spectral satellite instruments, like SeaWiFS, MERIS and MODIS provide sufficient spectral information to separate surface and aerosol contribution from the top-of-atmosphere (TOA) reflectance. This separation needs a-priori knowledge about the surface reflectance, which can be estimated from multi-spectral satellite observations. Methods applicable for the retrieval of AOT over land are several: (1) The 'dark dense vegetation' (DDV)-approach, Santer et al., 1999, is restricted only to very dark dense vegetation, such as dark dense forests, where low values for the surface reflectance can be assessed. (2) The 'inter-correlation'-approach, Kaufman et al., 1997, especially for MODIS, uses empirical correlations between the channel at 2.1 μm and SW channels of 0.465 μm and 0.645 μm. Thus, the variability of the surface reflectance in two SW channels of MODIS can be determined over a wide variety of land surfaces. This enables the retrieval of AOT. (3) A tuned mixing of land surface reflectance spectrum, using the NDVI and two basic surface types 'bare soil' and 'green vegetation' is used by the BAER approach (Bremen AErosol Retrieval), von Hoyningen-Huene et al., 2003, to estimate the spectral surface reflectance for wavelengths <0.67 μm. This approach is working also over a wide variety of land surfaces with different degrees of vegetation cover, given by the NDVI (Normalized Differential Vegetation Index). Since MERIS Bezy et al., 2000 is not providing information at a wavelength at 2.1 μm, like MODIS, the BAER approach is used for the retrieval of AOT and the atmospheric correction of land surface reflectance spectra for MERIS L1 and L2 data. However, MERIS provides 15 well calibrated spectral bands, not going into saturation over land. Seven of these bands are below 0.67 μm, giving sufficient spectral information for a retrieval of spectral AOT over land. Thus MERIS data yield that information content, required for aerosol remote sensing. The MERIS L1 product gives top-of-atmosphere (TOA) radiance for each spectral channel, from which TOA reflectance for the retrieval is obtained. The MERIS L2 product is an inhomogeneous product. It is made for user communities focused on ocean and land surface properties. It gives an atmospherically corrected surface reflectance, however, for ocean only. Over land Rayleigh path reflectance has been corrected only, aerosol is not considered. Therefore atmospheric correction over land requires the retrieval of AOT.

The paper gives a short description of the general method and demonstrates its applicability for the retrieval of spectral AOT and its application for the determination of the atmospheric corrected surface reflectance spectra, using MERIS observations. Compared with von Hoyningen-Huene et al., 2003, the AOT retrieval is improved in terms of a more correct consideration of the surface term, especially by the use of modeled hemispheric reflectance and total transmissions for aerosol and Rayleigh scattering, as given in Hoyningen-Huene et al., 2006. Additionally, spectral surface reflectance, obtained by atmospheric correction is considered. The specific approach for MERIS L2 data over land surface is described by Hoyningen-Huene et al. (2005).

2. Description of the methods

The retrieval method used over land consists of 2 parts: (1) The retrieval of the spectral AOT, based on data of TOA reflectance from MERIS channels 1–7 (0.412–0.665 μm) and using a surface reflectance model for the short-wave-channels of MERIS. The approach with its main equations is described briefly within the next paragraph. A more complete description of the BAER approach, can be found in von Hoyningen-Huene et al., 2003. (2) The atmospheric correction, calculating Rayleigh path reflectance, aerosol path reflectance and hemispheric reflectance for the determination of the spectral surface reflectance. Since the retrieval can give AOT for the first seven shortwave channels of MERIS, AOT must be extrapolated to all MERIS channels over the whole spectral range from 0.412 to 0.885 μm, using an Angström power law. The Angström parameters are derived by spectral AOT of the channels 1–7. Using the AOT in the whole spectral range, aerosol reflectance for all channels can be obtained and corrected. The overall scheme of the combined retrieval of AOT and surface reflectance is presented in the scheme in Fig. 1.

Both steps, the retrieval of AOT and the atmospheric correction rely on the representation of the TOA reflectance $\rho_{\mathrm{TOA}}(\lambda)$ by the solution of the radiative transfer equation for the aerosol reflectance $\rho_{\mathrm{Aer}}(\lambda)$. This is the main part of BAER. In particular, we use the following equation for $\rho_{\mathrm{Aer}}(\lambda)$ (Kaufman et al., 1997; von Hoyningen-Huene et al., 2003):

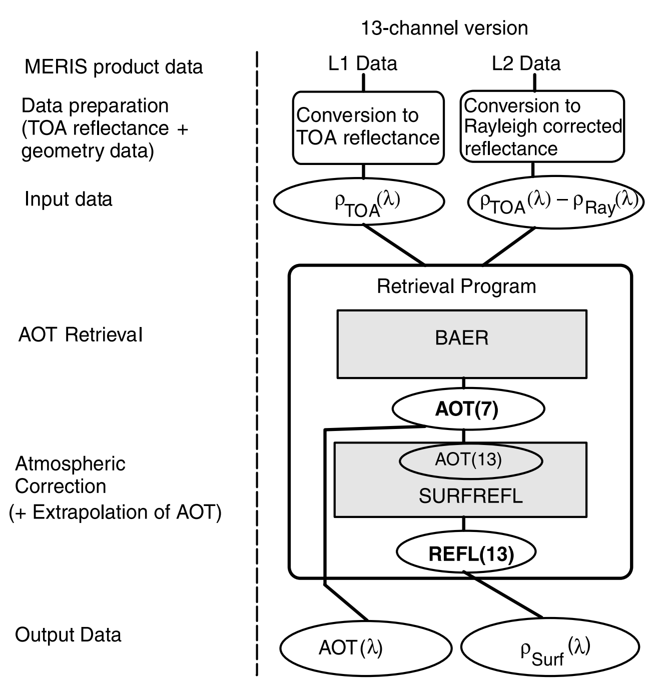

Fig. 1. Scheme of the processing program for the AOT retrieval and subsequent determination of spectral surface reflectance from MERIS L1 and L2 data. The numbers in the parenthesis are the number of channels available.

$$\rho_{\mathrm{Aer}}(\lambda,z_O,z_S) = \rho_{\mathrm{TOA}}(\lambda,z_O,z_S) - \rho_{\mathrm{Ray}}(\lambda,z_O,z_S,p_{\mathrm{Surf}}(z)) - \frac{T(\lambda,M(z_S))\cdot T(\lambda,M(z_O))\cdot A_{\mathrm{Surf}}(\lambda,z_O,z_S)}{1-A_{\mathrm{Surf}}(\lambda,z_O,z_S)\cdot\rho_{\mathrm{Hem}}(\lambda,z_O)}. \quad (1)$$

$T(\lambda, M(z))$ is the total atmospheric transmission for the zenith distance z, containing direct and diffuse transmission for illumination z_O and viewing geometry z_S, M is the air mass factor for sun and viewing geometry. $\rho_{\mathrm{Ray}}(\lambda,z_O,z_S,p_{\mathrm{Surf}}(z))$ is the path reflectance of the Rayleigh scattering and $\rho_{\mathrm{Hem}}(\lambda,z_O)$ is the hemispheric atmospheric reflectance. Total transmissions and hemispheric reflectance are determined by parameterizations derived from radiative transfer calculations, see Hoyningen-Huene et al., 2006. For the determination of AOT in step 1, a surface reflectance $A_{\mathrm{Surf}}(\lambda,z_O,z_S)$ must be given by a mixing model of the 'green vegetation' $\rho_{\mathrm{Veg}}(\lambda)$ and the 'bare soil' $\rho_{\mathrm{Soil}}(\lambda)$ spectra

$$A_{\mathrm{Surf}}(\lambda) = F\cdot[C_{\mathrm{Veg}}\cdot\rho_{\mathrm{Veg}}(\lambda) + (1-C_{\mathrm{Veg}})\cdot\rho_{\mathrm{Soil}}(\lambda)] \quad (2)$$

with $C_{\mathrm{Veg}} = \mathrm{NDVI}$, the vegetation fraction using an atmospheric corrected NDVI, and the scaling factor F for the level of the surface reflectance determined at 0.665 μm

$$F = \frac{\rho_{\mathrm{TOA}}(0.665) - \rho_{\mathrm{Ray}}(0.665) - \rho_{\mathrm{Aer}}(0.665)}{C_{\mathrm{Veg}}\cdot\rho_{\mathrm{Veg}}(0.665) + (1-C_{\mathrm{Veg}})\cdot\rho_{\mathrm{Soil}}(0.665)}. \quad (3)$$

Thus, for the shortwave channels the surface reflectance can be estimated on a pixel by pixel basis directly from the satellite scene and the variable surface reflectance over land surfaces can be considered in the determination of the aerosol reflectance.

For ocean conditions, a similar approach is used, based on spectra of 'clean water' and 'coastal water', tuned by the NDPI (Normalized Differential Pigment Index) instead of the NDVI. NDPI is defined as $NDPI = (\rho_{\mathrm{TOA}}(0.443\ \mu m) - \rho_{\mathrm{TOA}}(0.560\ \mu m))/\rho_{\mathrm{TOA}}(0.490\ \mu m)$.

AOT is then determined by look-up-tables (LUT), giving the relationship between aerosol reflectance and AOT. LUTs are obtained by radiative transfer calculations with given aerosol phase functions and single scattering albedos. Here experimental data from the LACE-98 experiment are used, as described by von Hoyningen-Huene et al., 2003. The use of phase functions and single scattering albedo of LACE-98 fixes the AOT retrieval to an aerosol type described by these optical properties. Since the used phase function and single scattering albedo affect primarily the magnitude of AOT only, the spectral variation of AOT is determined by TOA reflectance, Rayleigh scattering, surface elevation, surface reflectance and geometry. However, the use of seven spectral channels with wavelengths <0.67 μm of the MERIS instrument enables the determination of the variable spectral slope of AOT, indicating different aerosol types. Thus, the spectral slope clearly indicates coarse or fine aerosols. Thus classifications of magnitude of AOT and spectral slope in a subsequent step yield an information on aerosol type, without assessing this in advance.

Since the sensitivity of TOA reflectance against AOT depends on surface albedo, LUTs for different surface albedos are required. The present LUTs cover a range in surface reflectance from 0 to 0.3. The sensitivity for AOT decreases with increasing albedo. However. with the knowledge of surface reflectance the appropriate LUT can be selected to derive AOT.

After the determination of AOT the surface reflectance is derived from the TOA reflectance for all MERIS channels, using the solution of Eq. (1). The surface term is obtained as follows:

$$A_{\mathrm{Surf}}(\lambda) = \frac{\rho^*(\lambda)}{T(\lambda, M_S) \cdot T(\lambda, M_O) + \rho^*(\lambda) \cdot \rho_{\mathrm{Hem}}(\lambda, z_O)}, \qquad (4)$$

where

$$\rho^*(\lambda) = \rho_{\mathrm{TOA}}(\lambda, z_O, z_S) - \rho_{\mathrm{Ray}}(\lambda, z_O, z_S, p_{\mathrm{Surf}}(z)) - \rho_{\mathrm{Aer}}(\lambda, z_O, z_S).$$

The term $\rho^*(\lambda) \cdot \rho_{\mathrm{Hem}}(\lambda, z_O)$ in Eq. (4) can be neglected, because it is in the most cases close to 0, except for very bright grounds. For surface reflectance smaller than 0.1 the term is 0.01. In the case of bright surface reflectances of about 0.3 the term is equal to approximately 0.1, leading to an underestimation of surface reflectance, if the product $\rho^*(\lambda) \cdot \rho_{\mathrm{Hem}}(\lambda, z_O)$ is neglected. With Eq. (4), the second step the atmospheric correction is performed.

3. Results

Using the approach, described in Section 2, spectral AOT and surface reflectance can be determined from MERIS reduced resolution (RR) L1 and L2 data with a spatial resolution of 1.2 km ground pixel size. Even full resolution data (FR) with a spatial resolution of 0,3 km can be treated by the technique described above. Results of this approach are presented here for the scene of the 21 August 2002 over northern Germany. Fig. 2 gives the regional pattern of AOT for the wavelength of 0.412 μm. The obtained AOT is comparable with ground-based AERONET measurements of the site at Helgoland and Sopot and the measurements of the German Weather Service (DWD) at Zingst. A correlation plot for two channels (0.443 and 0.665 μm) against AERONET data, cf. Holben et al., 1998, for scenes of August/September 2002 (including this scene) is presented in Fig. 3. For low AOT, the correlation plot gives a quite good agreement and nearly a 1:1 relationship between retrieved and ground-based values. For high AOT (>1), BAER gives an underestimation of about 20%. This could be caused by the fact that aerosol absorption effects are not considered in this case. Polluted situations will have a significant soot content and a decreased single scattering albedo, which is assumed to be equal to 1 in this paper.

The spectral AOT for selected targets is presented in Fig. 4 in a double logarithmic plot. Clearly, one can recognize from the spectra different atmospheric conditions. (1) One group of spectra have a flat spectral slope. They are single spots within the scene and we believe, that these spectra are related to the small sub-pixel clouds, which are not detected by the regular cloud screening procedures used in the processing of the L2 data, distributed by ESA. (2) The most spectra have the expected spectral slope for aerosol. AOT decreases with the wavelength in a nearly power law, from which the Angström α-parameter can be derived, used for the extrapolation of AOT to the NIR in the later atmospheric correction step. (3) In cleaner conditions the spectra of the AOT in this double logarithmic plot contain more relative disturbances. The spectra do not have smooth slopes, like for the case of increased AOT.

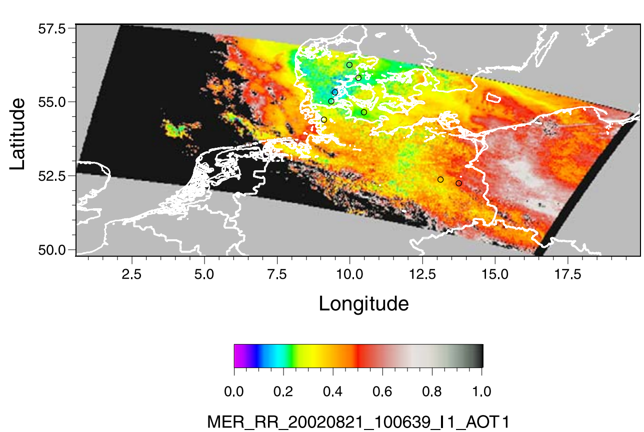

Fig. 2. Retrieved AOT for the MERIS channel 1 (0.412) μm obtained using BAER approach for scene of the 21 August 2002. Black circles indicate the regions, where spectra of AOT and surface reflectance in Figs. 4 and 5 are selected.

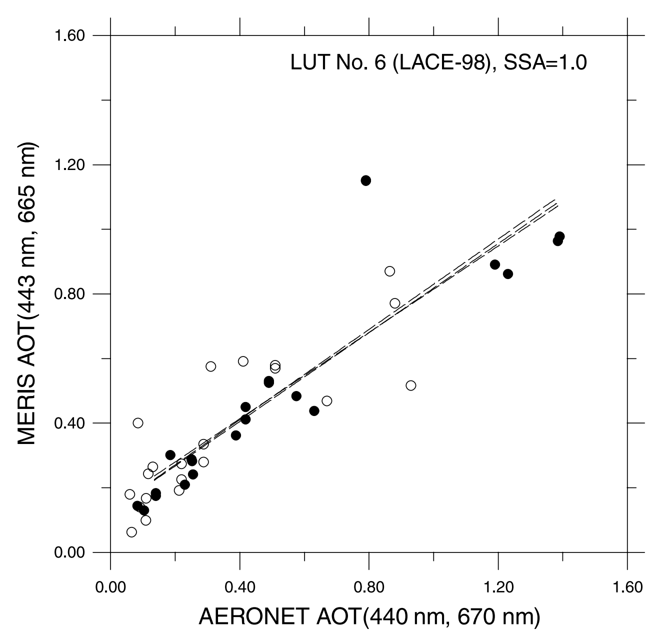

Fig. 3. Comparison of retrieved and ground-based AOT for channel 2 (0.443 μm, full dots) and channel 7 (0.665 μm, open circles) with comparable AERONET channels (0.440 and 0.670 μm), using MERIS RR scenes over Europe of August and September 2002.

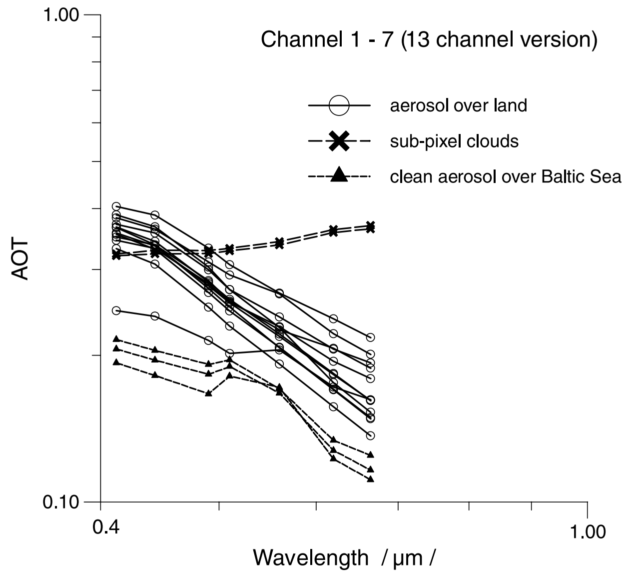

Fig. 4. Spectra of retrieved AOT from the MERIS scene of the 21 August 2002.

Especially for condition over the Baltic Sea we observe increased AOT in MERIS channels 4 and 5 at 0.510 and 0.560 μm. This can be connected with a not proper consideration of real water properties of the Baltic sea. Especially these both channels are disturbed by chlorophyll concentrations. Since the focus of BAER is more on land surface properties these effects are not investigated in detail.

In Fig. 5 one can find spectra of the surface reflectance. In the blue spectral range all spectra have decreasing reflectance with decreasing wavelength. Using the extrapolation of the AOT to the NIR channels of MERIS atmospheric correction also for the wavelength larger than the red edge and in the NIR range have been performed. Thus, spectral features of the surface targets are obtained. One can distinguish clearly different types of spectra over land.

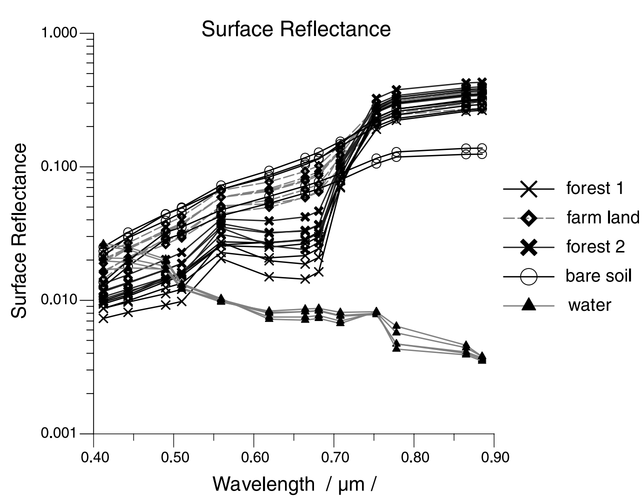

Fig. 5. Derived spectra of surface reflectance, using atmospheric correction including AOT from BAER retrieval for selected targets of the MERIS scene of the 21 August 2002.

The chlorophyll peak at 0.560 μm can be observed for targets with a high degree of green vegetation. Dark dense vegetation of forests can be recognized. Also farm lands with low vegetation or a high bare soil fraction can be seen. Ocean spectra can be derived, if MERIS L1 data are used.

A check for the comparability of the atmospheric correction is made, using the atmospheric correction of the SMAC processor Rahman and Dedieu, 1994. Compared with the SMAC results for comparable targets this approach gives lower values for the surface reflectance. In the NIR the underestimation is about a factor of 0.9, in the VIS it is 0.8. This is caused by the different aerosol parameters (phase function and single scattering albedo), used in both approaches for the atmospheric correction. SMAC uses a continental aerosol type. Our approach is based on experimental phase functions and single scattering albedo from LACE-98, von Hoyningen-Huene et al., 2003 and considers the real spectral slope, derived by the retrieval. Since in SMAC the reference wavelength of AOT is 0.5 μm, an overestimation of AOT (relatively increased surface reflectance) for smaller wavelength can occur. In the NIR the opposite can be the case. However, here the neglected term in Eq. (4) can be the reason for the differences. Therefore the complete Eq. (4) will be used for future applications.

4. Conclusion

With the results presented, it is obvious, that the BAER approach is able to derive AOT (over both, land and ocean) in the seven shortwave MERIS channels. The spectral AOT is comparable with ground-based measurements from AERONET. In both magnitude and spectral slope the retrievals are comparable. Therefore, the spectra could be extrapolated to the NIR region of the MERIS data, using an Angström power law, derived from the retrieved section of the spectrum. Thus, for the whole spectral range of MERIS, the AOT is derived.

Although only one experimental aerosol phase function (LACE-98) is used, the spectral behavior of AOT as main information on aerosol type can be obtained correctly. The comparison with AERONET measurements shows, that magnitude is in correct range too. The mean fit error for AOT(0.443 μm) is 0.16.

Underestimation of AOT occurs, if a high soot content of aerosol can be expected, like in strongly polluted regions. This needs an independent information on single scattering albedo, which cannot be obtained from MERIS.

The AOT retrieval is limited to surfaces with the reflectance less than 0.2 in the blue channels. This is the case for the most regions. The decreasing sensitivity against AOT for increased surface reflectance leads to increased errors of AOT for longer wavelengths.

For brighter grounds, like bright bare soils, specific LUTs will be required. These are presently not covered by the approach. For snow and ice cover, the approach cannot be used.

Ocean conditions are only considered marginally. The main focus was on land surface.

With derived AOT the atmospheric correction is performed and spectra of the surface reflectance are obtained. A general problem consists of the validation of spectral surface reflectance retrievals. It should be compared with spectra from ground-based sites. Unfortunately no suitable ground-based sites provide surface spectra for comparisons. Therefore for validation only other retrievals, that of SMAC, is used. The validation of surface reflectance, using SMAC, lacks in bad comparability of the aerosol type. SMAC uses the continental aerosol model only. BAER, however, considers the retrieved spectral slope. This is an improvement against fixed aerosol types, which are not verified by the retrieval. Thus, even surface properties could be derived under thin Ci cloud, which have been comparable with spectra outside of this disturbance.

The approach described above will be implemented within the next version of the BEAM toolbox, provided by ESA, see BEAM WEB-Page, 2004. Thus, the presently missing step of atmospheric correction of land surface reflectance in L2 data can be accomplished.

The general approach, presented here, is applicable for the generation of aerosol products from L1 data, giving AOT in unique way both over land and ocean. Thus, different approaches for the derivation of the AOT over ocean and land can be unified, avoiding discontinuities in the AOT pattern between ocean and land retrievals.

Acknowledgements

The authors express their thanks to ESA and BMBF supporting the development of the aerosol retrieval over land and its application for atmospheric correction. We appreciate the comments of the reviewer, helping to improve the contribution.

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